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Assessing impact of topographic and climatic factors on radial standard growth for 4 temperate species in South Korea

Moonil Kim[a,b], Woo-Kyun Lee[a*], Yowhan Son[a]

[a]*Division of Environmental Science & Ecological Engineering, Korea University, Seoul, 136-701, Republic of Korea.*

[b]*International Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria*

*Corresponding author: Woo-Kyun Lee

Email: leewk@korea.ac.kr

Tel: +82-2-3290-3016

Fax: +82-2-3290-3470

Abstract

Annual diameter growth of trees is vital for the assessment of site suitability and potential timber yield. However, quantitative relationships between tree growth and environmental factors, such as climatic and topographic factors, are not well understood. The main objective of this study was to develop a tree-level growth model considering topographic and climatic factors for four major temperate tree species [red pine (*Pinus densiflora*), oak (*Quercus* spp.), Japanese larch (*Larix kaempferi*), and Korean pine (*Pinus koraiensis*)] in South Korea to estimate annual radial growth. The model was developed and validated using a total of 43,532 increment cores sampled from country wide permanent plots in the Korean National Forest Inventory. The growth data were constructed from recent radial growth from 1996 to 2005 for each increment core. The standard growth (SG), which eliminated the tree age effect on radial growth, of each increment core was derived using a standard growth model. Spatial autocorrelation was detected from SGs of every species, but not for in original radial growth data. The results showed that using the SG model to standardize radial growth for age was successful. Variation in SGs could be explained by regional variables, such as topographic and climatic factors, with spatial autocorrelation. The influence of climatic (warmth index, precipitation effectiveness index) and topographic (topography wetness index) on SG of each species was evaluated by the estimated SG (eSG) model using a generalized additive model. For all species analyzed, each variable in the eSG model accounted for significant amounts of the variation in SG. The mean R^2 of final radial growth model for red pine, oak, Japanese larch, and Korean pine during 2001–2005 were estimated as 0.70, 0.72, 0.65, and 0.63, respectively. In addition, the time sequence of estimated annual radial growth exhibited a similar trend with that of an observed annual radial growth on an individual tree scale in every tree species. In particular, lower annual radial growth of trees because of the severe drought in 2001 was accurately predicted. In addition, the eSG model could be used to evaluate the site suitability for the cultivation of selected species and availability of potential timber yield information. Thus, this growth model could tour understanding of the impacts of environmental factors on tree growth and prediction the annual growth changes in major tree species in terms of climate change in South Korea.

Key words: *radial growth, national forest inventory, climate change, precipitation effectiveness index, warmth index, topographic wetness index*

1. Introduction

The prediction of tree growth for forest planning and management is typically achieved by considering environmental factors, such as precipitation, temperature, drought, and soil and topographic characteristics (Schweingruber, 1988). This approach has a long tradition among foresters, particularly when the climatic parameters are recognized as major abiotic factors influencing the phenological, physiological, and geographical states of the forest ecosystem (Box, 1996). However, climate observations are currently exhibiting a global warming trend; global average temperatures increased by 0.8°C since 1900 (Hansen et al., 2006), and the 12 hottest years on record have all occurred between 1990 and 2005. Consequently, the uncertainty in the estimation of future forest resources has increased.

Tree growth is an important facet of forest dynamics, which can inform the health, productivity, and sustainability of a forest, as well as the spatial and temporal variability in growth rates. Dynamics that depend on a clear understanding of tree growth include species interactions (Swetnam and Lynch, 1993), carbon sequestration (Caspersen et al., 2000; DeLucia et al., 1999), population dynamics (Webster and Lorimer, 2005), and forest restoration (Pearson and Vitousek, 2001). It is therefore important to understand the relationships between forest growth and climatic factors for proper forest management, while coping with global warming and climate change.

The increment core is a method for estimating tree growth. Tree ring growth has played a critical role in identifying the growth response of trees to environmental and climatic variation (Fritts, 1976). For example, studies in a wide range of forest environments have shown that variation in tree ring width is correlated with variation in macroclimate (Takahashi et al., 2003). Accordingly, tree ring data have been used extensively in the development of tree growth models. Radial increment models are a fundamental component of forest growth and yield frameworks, and the development of such models is supported by large research bodies (Adame et al., 2008; Sterba et al., 2002; Trasobares et al., 2004); thus, radial growth models have been constructed for a wide range of forest regions and management scenarios.

Many existing tree growth models incorporate several factors that can affect tree growth (age and size of individual trees, topography, and climate). Incorporating age and size into growth models is necessary because growth rates can vary according to age and size of trees (Enquist et al., 1999; Enquist, 2002). Climatic and topographic factors serve to localize growth models to specific regions (Moore et al., 1993; Sørensen et al., 2006; Zirlewagen et al., 2007). In addition, changes in tree growth over time can be explained by both tree age and climatic factors (Ryan et al., 2008).

However, most models do not sufficiently meet the requirements of large-scale forestry scenarios that can be applied to a country or country wide analyses on the property level. Some models are based on locally relevant or insufficiently representative data, whereas others are adapted to certain treatments, and still others account for only one or a few tree species of interest. Another major limitation of previous research is that most has been quantitative rather than qualitative. A model based on quantitative analysis of tree growth is essential to accurate prediction of forest growth and yield in support of decision making in forestry.

The main goals of this study were to develop a model to simulate tree-level radial growth for temperate forests in South Korea and to evaluate the effects of climatic and topographic factors on diameter growth. To achieve these objectives, permanent sample plots recorded by the Korean National Forest Inventory (NFI), standard growth model, semi-variogram analysis, and generalized additive model (GAM) were applied. This model can be used to predict forest growth according to climatic change for entire forests across South Korea.

2. Materials

2.1. Study area

The study area included all of South Korea's forests (longitude 124°54′–131°06′ and latitude 33°09′–38°45′; Figure 1). The Taebaek Mountain Range rises to over 1,500 m on the eastern side of Korea and then drops steeply toward the East Sea with a narrow coastal plain. From the Taebaek Mountain Range, the Sobaek Mountain Range runs from the northeast to the southwest. In the central zone, moderately high mountains dominate the landscape. Lowlands are found primarily along the western region of the study area (Figure 1b). Approximately 64% (6,368,844 ha) of South Korea is covered with forest. Red pine (*Pinus densiflora*), Japanese larch (*Larix kaempferi*), Korean pine (*Pinus koraiensis*), and oak (mainly *Quercus variabilis* and *Quercus mongolica*) were the major tree species. These tree species form large forests in most of the mountainous areas of South Korea, and occupied approximately 37%, 5%, 4%, and 16%, respectively, of the total forested area in 2010.

<Figure 1>

2.2. Dataset and measurement protocols

The tree ring dataset used in this study was taken from the 5th South Korea NFI, which was conducted from 2006 to 2010 for all South Korea's forests (Figure 1b). The survey design consisted of systematic sampling at intervals of 4 km (longitude) × 4 km (latitude) across South Korea. Four circular sample plots were located at the intersection of each 4 km × 4 km grid line. Each year, 20% of grid locations were sampled, such that the entirety of South Korea was inventoried each year. The total inventory is comprised of 4,200 clusters, consisting of 16,800 permanent plots. Forest characteristics (tree species, age, and height), diameter at breast height (*dbh*), number of trees with a dbh greater than 6 cm, and topographical factors (coordinates, elevation, slope, and aspect) were measured at all permanent plots.

In each plot, increment cores were obtained from approximately six dominant or co-dominant trees. One core per tree was extracted from trees at breast height from a direction parallel to the slope using an increment borer. Cores were mounted, sanded and polished; ring width was then measured using a digital tree ring system (DTRS)-2000, which can determine annual tree ring width at a high resolution (up to 1/100 mm), by the Korea Forestry Promotion Institute. Tree-ring widths were measured carefully, and cross-dated using several numerical methods (Aniol, 1983; van Deusen, 1990), as well as visual comparison of tree-ring characteristics. In dendrochronological cross-dating, variations in ring widths are first examined and then synchronized among all available samples from a given region. Covariation among tree-ring series ensures the dating of each ring with an accuracy of one year. This synchronization of tree-ring series and cross-dating provides the annual dating control of examined characteristics (Fritts, 1976).

In this study, we used the 43,532 core samples from the five main temperate tree species in South Korea (Table 1), which include red pine (*Pinus densiflora*), Japanese larch (*Larix kaempferi*), Korean pine (*Pinus koraiensis*), Chinese cork oak (*Quercus variabilis*), and Mongolian oak (*Quercus mongolica*). These tree species form large forests in most of the mountainous areas in South Korea, and occupied approximately 37%, 5%, 4%, and 25%, respectively, of the total forested area in 2010. The available data for each species were divided into two sets: data obtained in 2006–2008 were used to estimate model parameters and the remaining data (2009–2010) were reserved to validate the models (Table 1).

<Table 1>

2.3. Climatic data preparation

Climate data were collected from recent years (1996–2005). The Korean Meteorological Administration (KMA) provided climatic data from 75 weather stations from this period. These data were interpolated with a 0.01° grid size (about 1 km) using the interpolation methods of kriging and inverse distance squared weights (IDSW) considering absolute temperature and precipitation lapse rate by altitude (Cho et al., 2011; Yun et al., 2001).

3. Methods

3.1. Entire process

This study was performed following the four steps shown in Figure 2. First, we calculated the standard growth (SG) of individual samples according to species. The SG, the potential radial growth at age 30, was used to standardize the radial growth of tree rings from a variety of ages. In the second step, we evaluated the spatial autocorrelation of SG for the four major tree species. Third, we calculated the estimated standard growth (eSG) by analyzing the relationship between SG and climatic and topographic factors using a GAM. The eSG can explain the influence of topographic and climatic factors on radial growth. In the fourth step, an annual radial growth model was developed and validated using the tree core dataset.

<Figure 2>

3.2. Factors and variables

One of the goals of the present study was to identify the climatic and topographic factors that could be used to develop a growth model. The influence of climatic and topographic factors on tree growth was evaluated by multiple regression analysis and climatic and topographic indices, which were closely related to tree physiology. Temperature, precipitation, and topographic conditions have been recognized as major factors affecting tree growth and physiology. Therefore, the warmth index (WI) (Kira, 1945; Yim, 1977), the precipitation effectiveness index (PEI) (Thornthwaite, 1948), and topographic wetness index (TWI) (Moore et al., 1993) were selected to assess the influence of environmental conditions.

WI is the summation of monthly mean temperatures (t, in °C) with 5°C as the threshold [i.e., $WI=\sum(t - 5)$] and where the summation is only made for the months in which $t > 5$°C (Kira, 1991). This index has been shown to match the distribution of vegetation types and tree growth in East Asia, including South Korea (Choi et al., 2011; Umeki, 2001). The PEI is equal to the sum of monthly precipitation-evaporation ratios (PE ratio: ratio of the monthly precipitation amount to monthly evaporation). The PEI is a measure of the long-range effectiveness of precipitation in promoting plant growth for a given location. The PEI has been used to classify the climatic zone corresponding to forest ecosystem types (Thornthwaite, 1948) and to demonstrate the relationship between a hydrological index and vegetation regimes (McCabe and Wolock, 1992). We used the summer (June to August) PEI instead of the annual PEI because the annual PEI did not incorporate seasonal variation, which is important because of the establishment and radial growth of tree species associated with seasonal climatic features. Based on previous research, precipitation in summer (June to August) is positively correlated with annual radial growth of *P. densiflora* (Lee et al., 2008), *Quercus* spp. (Shin, 2006; Shin et al., 2008), and *P. koraiensis* (Lee et al., 2009).

Topographic and soil moisture conditions are also very important determinants of tree growth and vegetation composition. Several topographic-based indices of soil moisture have been proposed in previous years (Iverson et al., 1997; Murphy et al., 2009); however, the most popular indicator is the topographic wetness index (TWI). This index is defined as $TWI = \ln(As/\tan \beta)$. The TWI uses the surrounding topography to describe a location’s ability to become saturated; TWI has been shown to be correlated with soil attributes, including horizon depth, silt percentage, and organic matter (Moore et al., 1993). TWI has also been used as a predictor variable of forest health conditions (Zirlewagen et al., 2007).

3.3. Evaluation of diameter growth

In dendroclimatological studies of multi-aged forest stands, climate-growth relationships can be biased because different trees at any given time are responding differently to the climate depending on their age (Szeicz and MacDonald, 1995). In addition, the data from the Korean NFI reflected the full range of variability with respect to its sites, forest structure, and tree species. To overcome these limitations, two methodological approaches were adopted. In the first method, the radial growth data from the individual increment core samples were rebuilt. The core samples from Korean NFI had a high variation in radial growth. To reduce uncertainties in the raw data, the mean radial growth data for the most recent 10 years (1996–2005) were used to construct a growth model and to analyze the effects of climatic and topographic factors on radial growth in this study.

$$\Delta MR_{ij} = \sum_{k=1996}^{2005} AR_{ijk}\ (mm) \qquad (1),$$

where i is the identification number of the NFI plot, j is the unique number of each tree in one NFI plot, AR is the annual radial growth at k year, k is the year, and MR is mean radial growth of each tree from 1996 to 2005.

In the second step, the SG model was adopted to remove the growth trends from raw ring-width series. The SG model is a standardization technique that uses the detrending method and algebraic differences form (Byun et al., 2010). The SG model is composed of a three-step process. First, it applies the following power function (Equation 1) to extract general growth patterns for each species associated with tree age. Second, SG was defined as the radial growth at a specific age. In this study, mean age of Korean trees (age 30) was applied to SG. Third, to convert the ΔMR from various tree ages to the SG at age 30, the transformation to algebraic differences form was applied by integrating equations 1 and 2, as shown in equation 3.

$$\Delta MR_{ij} = a \cdot age_{ij}^{b} \tag{2}$$

$$SG_{ij} = a \cdot 30_{ij}^{b} \tag{3}$$

$$SG_{ij} = \Delta MR_{ij} \cdot \left(\frac{30}{age_{ij}} \right)^{b} \quad (4),$$

where SG is the estimated radial growth at age 30, and a and b are coefficients.

The use of SG makes it possible for individual trees to be compared under the same conditions by eliminating effect of tree age on tree growth. Therefore, the variation of SGs for each tree species can be explained by environmental conditions, such as climatic and topographic factors. The relationship between SG and climate and topography can be analyzed quantitatively, without age-dependent responses of tree-ring growth to environmental conditions.

3.4. Spatial autocorrelation

Any spatial scales for climate will present spatial patterns. Therefore, although the SG model had a good statistical fit, the SGs can exhibit spatial autocorrelation if climate influences tree growth. Therefore, we evaluated and compared the spatial autocorrelation of ΔMRs and SGs. ‘Spatial autocorrelation’ is the correlation among values of a single variable strictly attributable to their relatively close locational positions on a two-dimensional (2-D) surface, introducing a deviation from the independent-observation assumption of classical statistics. Spatial autocorrelation exists because real-world phenomena are typified by orderliness, (map) patterns, and systematic concentration, rather than randomness.

If differences in SGs exist at the regional level as a result of other factors, such as climatic or topographic factors, the SGs will exhibit spatial autocorrelation. We used the semi-variogram analysis to identify spatial autocorrelation (Bahn et al., 2008). In this paper, the semi-variograms used were all fitted to the spherical model (Vieira, 2000). We also estimated additional spatial parameters in SDGs, in which spatial autocorrelation was included, using the SPATIAL STATS sub-module in the S-PLUS program (Kirilenko and Solomon, 1998).

According to existing studies, tree growth is associated with climatic water/heat stress (Byun et al., 2013). This demonstrates that if spatial autocorrelation is found in SGs, the relationship between SG and climatic factors can be analyzed quantitatively.

3.5. Model structure development

Growth data were sorted by species and the following model was applied to each species to extract growth patterns associated with climatic and topographic factors (Eq. 5). The models were analyzed using a GAM with a spline function (SAS Institute, 2008). The GAM is a nonparametric extension of the generalized linear model (GLM) and has been increasingly used in ecological studies (Austin, 2002; Guisan and Edwards, 2002; Guisan and Zimmermann, 2000).

$$SG_{ij} = \beta_1 \cdot WI_i^2 + \beta_2 \cdot WI_i + \beta_3 \cdot PEI_i^2 + \beta_4 \cdot PEI_i + \beta_5 \cdot TWI_i + Int \qquad (5)$$

where *i* is the identification number of the NFI plot, *j* is the unique number of each tree in one NFI plot, *WI* is the warmth index, *PEI* is the precipitation effectiveness index, *TWI* is topographic wetness index, *Int* is an intercept, β_0, β_1, β_2, β_3, and β_4 are the estimated parameters from the GAM.

Temperature and precipitation jointly determine the large-scale patterns of distribution and growth of woody plants (Hansen et al., 2001). For example, low temperatures directly affect trees by limiting energy for biochemical processes, decreasing membrane permeability, and increasing the viscosity of protoplasm; in contrast, excessive temperatures can denature or inactivate enzymes and decrease carbohydrate pools through high respiration rates (Kozlowski and Pallardy, 1997; Lambers et al., 1998). Accordingly, we modeled the relationship between climatic factors and tree growth using a non-linear quadratic function. However, we applied TWI as a linear function based on previous research (Dean et al., 2004; Zirlewagen et al., 2007).

The estimated SG (eSG) of each tree was computed by Eq. 5. It is defined as expected radial growth at 30 years of age under the environmental conditions of the tree's location. Therefore, the spatial suitability for each species was assessed by eSG. In addition, the eSGs in one species can indicate relative site suitability for environmental conditions. In conclusion, it can be used as an independent variable in the growth model.

In this study, the radial growth model was developed to account for the effects of climatic and topographical factors on diameter growth using eSG (Eq. 6).

$$\Delta\hat{r}_{fj} = \Delta r_{pj} \cdot \left(\frac{age_{ij}}{age_{pj}}\right)^{b} \cdot \left(\frac{eSG_{fj}}{meSG_{p}}\right) \qquad (6),$$

where f is each year from 2001 to 2005, p is the base period (1996–2000), j is the identification number of each tree, $\Delta\hat{r}$ is the predicted annual radial increment at the breast height of a tree, Δr is the mean observed radial increment from tree core data during the base periods, eSG is estimated standard growth, $meSG$ is the mean estimated standard growth of each species during the base period, and *b* is a constant for each species from Eq. 3. In this study, the base period was the five years from 1996 to 2000. This model was applied to estimated annual radial growth of a tree from 2001 to 2005.

In this model, Δr_{pj} was considered to reflect the individual and tree-stand level growth conditions, which would include competition among trees, site index, and size. Growth conditions are major factors that influence the growth of individuals and community dynamics. The eSG_{fj} can be normalized using $meSG_p$. As the normalized eSG_{ik} is integrated into the radial growth model, we are able to estimate radial growth increments by topographic and annual climatic conditions.

We validated the estimated radial growth by comparing the observed annual growth from increment core data. The performance of the growth model in predicting annual radial growth was analyzed using the root mean square error (RMSE) and coefficient of determination (R^2).

4. Results and discussion

4.1 Estimation of standard growth

The coefficients for equation 1 are shown in Table 2. All coefficients were statistically significant. Coefficient *a* and *b* in equation 1 indicated the average radial growth (mm) in 1 year and the effect of aging on diameter growth. Coefficient *a* of red pine, oak, Japanese larch, and Korean pine was estimated as 5.39, 7.33, 11.56, and 8.83, respectively. Coefficient *b* of red pine, oak, Japanese larch, and Korean pine was estimated as -0.3, -0.39, -0.48, and -0.39, respectively. These results showed that diameter growth of Japanese larch is relatively high, whereas the growth rate of Japanese larch slowed more sharply with age than did the other main tree species. This result was similar to that shown in previous studies (Kim et al., 2010). Japanese larch is one of the most economically important tree species in Korea because it is fast growing, and therefore these results reflect reality in the Korean forest.

The coefficient of determination (R^2) suggested that approximately 9.3–20.4% of radial growth variability could be explained by age. The regression model for each species had a low R^2 value, which showed relatively good statistical performance in terms of the significance level of coefficients (Table 2). From the results, it could be inferred that age successfully reflected the trend of radial growth change observed for major forests in Korea at the national scale, whereas uncertainties remained for individual stand environments.

<Table 2>

4.2 Spatial autocorrelation

The spatial autocorrelation of the tree ring dataset and SG from equation 2 for each tree species is shown in the semi-variograms (Fig. 3). The range of semi-variogram of red pine, oak, Japanese larch, and Korean pine from tree ring datasets was estimated as 116.9, 98.3, 99.0, and 99.2 km, respectively. The partial sill values of these species were estimated as 0.0, 0.08, 0.0, and 0.0, respectively. This indicated that a very low degree of spatial autocorrelation was found in the tree ring dataset. Conversely, partial sill values were shown for SG in every species. The partial sill values of these species were estimated as 0.30, 0.19, 0.23, and 0.21, respectively. These results suggested that every species varied in their level of diameter growth because of other factors, with spatial autocorrelation in the range 30 to 50 km. Forests in South Korea cover a total area of 63,100 km^2 and have a complicated topography (Korea Forest Service, 2016). Therefore, this spatial autocorrelation may be associated with climatic rather than topographic factors.

These results showed that the general trend of tree growth with age in SG of each species was effectively eliminated. Therefore, the differences between each SG of tree ring data could be explained by regional climatic and topographic variables.

<Figure 3>

4.3 The distribution WI, PEI, and TWI in South Korea

The WI distribution for South Korea form 1996–2005 ranged from 34.8 to 148.0°C per month (mean 95.8°C; std. dev. 15.0) (Fig. 4a). These values corresponded to the criteria of Yim (1977): subalpine species (30–70°C per month), cool-temperate species (50–90°C per month), warm-temperate deciduous (80–100°C per month), and evergreen species zone (100–120°C per month). The WI distribution was likely related to latitudinal and altitudinal patterns, which were correlated with dominant tree species of forest ecosystems.

The summer PEI distribution ranged from 57.1 to 234.0 in/°F with a mean value of 156.6 in/°F (std. dev. 25.6) (Fig. 4b). The TWI distribution in South Korea ranged from 3.4 to 25.7 (mean 6.4; std. dev. 1.5) (Fig. 4c).

<Figure 4>

4.4 Estimated standard growth with GAM

Table 3 shows the statistical performance of the GAM analysis for examining the relationships between SG and WI, PEI, and TWI. All parameter estimates of the GAM analysis are logical and significant at the 0.05 level (Table 2). These results suggested that these indices had a significant relationship with diameter growth at the individual tree level. In each species, the *SG* tended to decrease when WI and PEI increased over a certain value (WI: [*P. densiflora*: 93.6, *Q*. spp.: 121.9, *L. kaempferi*: 74.8 and *P. koraiensis*: 79.6], PEI: [*P. densiflora*: 175.1, *Q.* spp.: 248.3, *L. kaempferi*: 130.6 and *P. koraiensis*: 153.2]) (Fig. 5). Consequently, the assumption about our eSG model match on the model results was confirmed. Different WI and

PEI thresholds among tree species suggested that the impact of temperature and precipitation on tree growth varies by species; it also inferred that climate change could alter the growth patterns and distribution of each species.

In Table 3, coniferous species had relatively larger absolute values for coefficients than did oak. This suggests that major coniferous species in South Korea could be more sensitive to changes in climatic conditions than oaks. These results are supported by previous studies showing that forest growth, cover, and mortality will change in South Korea because of future climate change (Byun et al., 2010; Choi et al., 2012; Kim et al., 2017). Kim et al. (2017) showed that increased tree mortality in Korean coniferous forests was associated with warmer conditions. However, the response of tree mortality differed among species as seen in the case of oak species, in which rising temperature tends to have a positive effect, although its level of significance has not been determined. This in part indicates that coniferous species could be more sensitive to climate change than oak species in South Korea.

In every species, the SG exhibited a positive correlation with TWI. A high TWI value is assigned to relatively flat locations with large up-sloping areas; these areas are expected to have relatively higher water availability than sloping locations with only a small upslope area (Beven and Kirkby, 1979; O'Loughlin, 1981). Sitter et al. (2012) reported that TWI values and vegetation index values were positively correlated, and Wang et al. (2004) demonstrated a strong relationship between normalized difference vegetation index (NDVI) and annual tree ring width. Therefore, the relationship between TWI and SG in our model is reflective of previous research.

In Fig. 5, the effects of each climatic and topographic factors on SG are illustrated. The coefficient of determination (R^2) suggested that approximately 2.5–8.5% of growth variability could be explained by climatic or topographic factors alone for tree species. Although each model had a low R^2 value, they described the relationship between overall radial growth patterns and each factor well.

In addition, the coniferous species (*P. densiflora*, *L. kaempferi*, and *P. koraiensis*) have a similar relationship between climate factors and *SG*, but a clear difference was seen in broad-leaved trees (*Quercus* spp.). In the case of coniferous species, they maximize their SG value under present climatic conditions, but *Quercus* spp. is projected to achieve a maximum SG value in future climatic conditions. This means *Quercus* spp. will do better than other coniferous trees in terms of growth in the future climate conditions and that coniferous trees could be potentially replaced by *Quercus* spp.

<Table 3>

<Figure 5>

4.5 Validation and application

4.5.1 Validation of the radial growth model

The estimated annual radial growth of each tree simulated by the developed growth model (Eq. 5) was compared with the observed annual radial growth of each tree core from 5th NFI (Korea Forestry Promotion Institute, 2013). The growth model explained a significant amount of variance (R^2 = 0.54–0.77) in radial growth from 2001 to 2005 (Table 4). The mean R^2 of red pine, oak, Japanese larch, and Korean pine was estimated as 0.70, 0.72, 0.65, and 0.63, respectively. In addition, the time sequence of estimated annual radial growth exhibited a trend similar to that of observed annual radial growth on an individual tree scale for every tree species (Fig. 6).

According to the observed annual radial growth from the 5th NFI, the mean radial growth of red pine, Japanese larch, and Korean pine increased from 1.90, 1.97, and 2.29 mm in 2001 to

2.03, 2.04, and 2.41 mm in 2002, respectively. The overall increment of annual radial growth in these tree species could be explained by climatic conditions. The year 2001 was a historical drought period in South Korea (KMA, 2001). In 2001, the mean annual precipitation was 997.3 mm, which was much less than the average of mean annual precipitation during 2002–2005 (1,518.7 mm). This indicated that drought occurred and had a critical impact on South Korea that led to regional water shortages. It also influenced the use of water, including agricultural and household activities (KMA, 2001). In addition, natural ecosystems were damaged from drought and vegetation indices on the national scale were low (Park et al., 2008). Because of these factors, annual radial growth of trees in 2001 was less than that in other years. However, the precipitation during 2002 was comparable to the annual average (KMA, 2002).

The estimated results showed that they increased from 1.83, 1.97, and 2.08 to 2.02, 2.14, and 2.43 mm, respectively, during that period. Because the results were similar, it could be inferred that the growth model appropriately reflected the annual radial growth according to climatic and topographic variables on regional and national scales.

The goal of this research was to develop a forest growth model to estimate temporal and spatial pattern of growth based on future climate change scenarios. For this research, we quantified how climate and geographical conditions affected the growth of each tree species based on tree core samples from NFI and developed the radial growth model. Although the model developed in this study was specific to our study region (South Korea) and forest type (mixed temperate), we believe that our approach can be easily applied to other regions where meteorological and geological data are available.

<Table 4>

<Figure 6>

4.5.2 Application of eSG

The eSG of each species means that potential radial growth reflected climatic and topographic conditions and was estimated spatially. Therefore, it could be used to assess capacity of site potential in terms of wood productivity, which is one of the most important aspects of land management from a forestry point of view. To address this, two simple steps were performed as follows: 1) The eSG of each species for the actual forest area derived from an actual vegetation map of Korea, which was produced by the Ministry of Korea in 2008, and the entire land area of South Korea was estimated to use equation 5, 2) the two results were compared.

Figure 7 shows the range of eSG in the actual distribution area for each species and the entirety of South Korea. For every species, the 95th percentile value of eSG in actual forest area for each species was higher than eSG in the entirety of South Korea. This result showed that most of the actual forest areas for each species was distributed where the eSG was thoroughly evaluated. It also revealed the success of the national reforestation project that the South Korean government implemented, the National Greening Program for the recovery of forests (Bae et al., 2012). These indicated that the eSG model could be used to evaluate the site suitability for the cultivation of selected species and the potential timber yield information, which is vital for the assessment of afforestation projects.

Japanese larch and Korean pine revealed that eSG ranges, the median value of actual forested areas and the entire country was significantly different. Conversely, this difference did not exist for red pine and oak. This showed that site suitability for Japanese larch and Korean pine in their actual distribution areas was very high. In addition, the growth and physiology (survival) of Japanese larch and Korean pine are more dependent on spatial and environmental conditions. This result is similar to findings of previous studies in South Korean forests. Kim et al. (2017)

found that the mortality of Japanese larch and Korean pine have been more strongly affected by temperature than red pine and oaks in South Korea.

These results lead to the conclusion that potential changes in forest community types in the South Korea will likely be significant under climate change. These potential changes, in turn, could have large impacts on regional biodiversity and the socioeconomics of the affected regions. The potential changes in species composition and forest structure will have major effects on the quality and quantity of valuable plant and wildlife habitats (Iverson and Prasad, 2001; Lindner et al., 2010; Schumacher and Bugmann, 2006). Therefore, forest management plans and silviculture practices need to be adapted to reflect changing climate patterns.

<Figure 7>

5. Conclusion

The objective of this study was to develop radial growth models for *P. densiflora*, *Quercus* spp., *L. kaempferi*, and *P. koraiensis* with the goal of radial growth in relationship to climatic and topographic factors. We used tree ring data, from the 5th NFI, and climatic and topographic data to develop the models. We developed a standard growth model and analyzed the relationships between SG and WI, PEI, and TWI using GAM.

Based on the semi-variogram of calculated SG for each tree species, all species showed clear spatial autocorrelation. This implied that climate and topography had an influence on growth of trees, and that SG effectively standardized growth of various aged trees. SG appeared to have a nonlinear relationship with the meteorological factors, and a linear relationship with TWI. However, TWI in this study had a weak influence on growth of forest trees, which led to a further study for supplementation. The coefficient of determination (R^2) of the growth model for each tree species derived in this study was 0.54–0.77, which was relatively high. In addition, the time sequence of estimated annual radial growth showed a trend similar to that of observed annual radial growth in four tree species.

Quantifying the relationship between tree growth and climate has been completed by various researcher groups; however, the results of these studies varied according to tree species, topography, climate, and methods, such that the relationship could only be explained by a few studies, including this one. Therefore, research issues related with such topics should proceed by examining various tree species and environmental factors in other regions. Our findings and predictions will be helpful for understanding the impact of climate factors on tree growth, and for predicting the distributional change of major tree species because of climate change.

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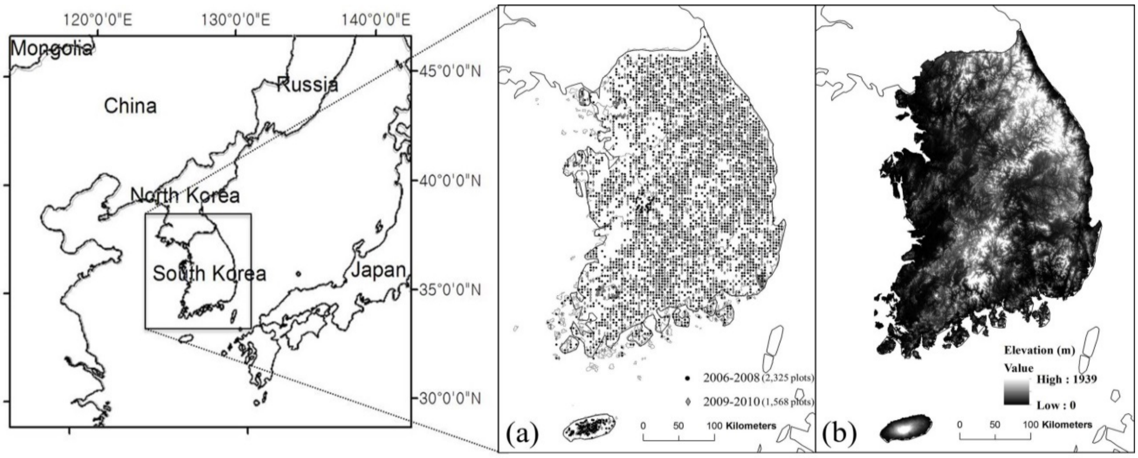

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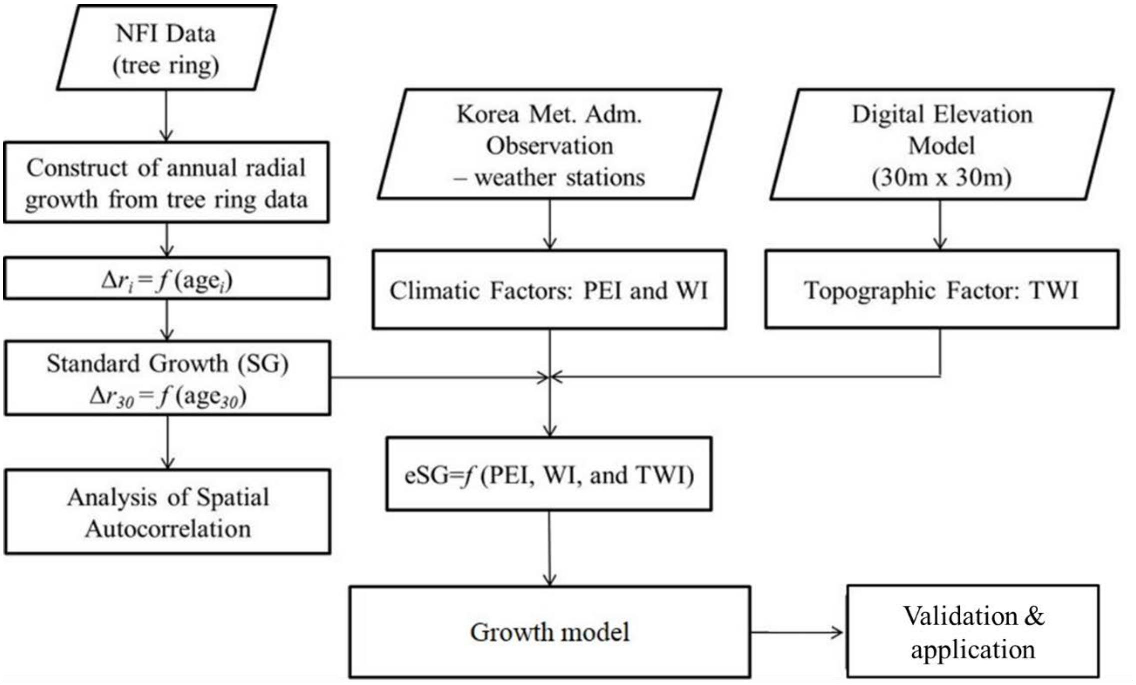

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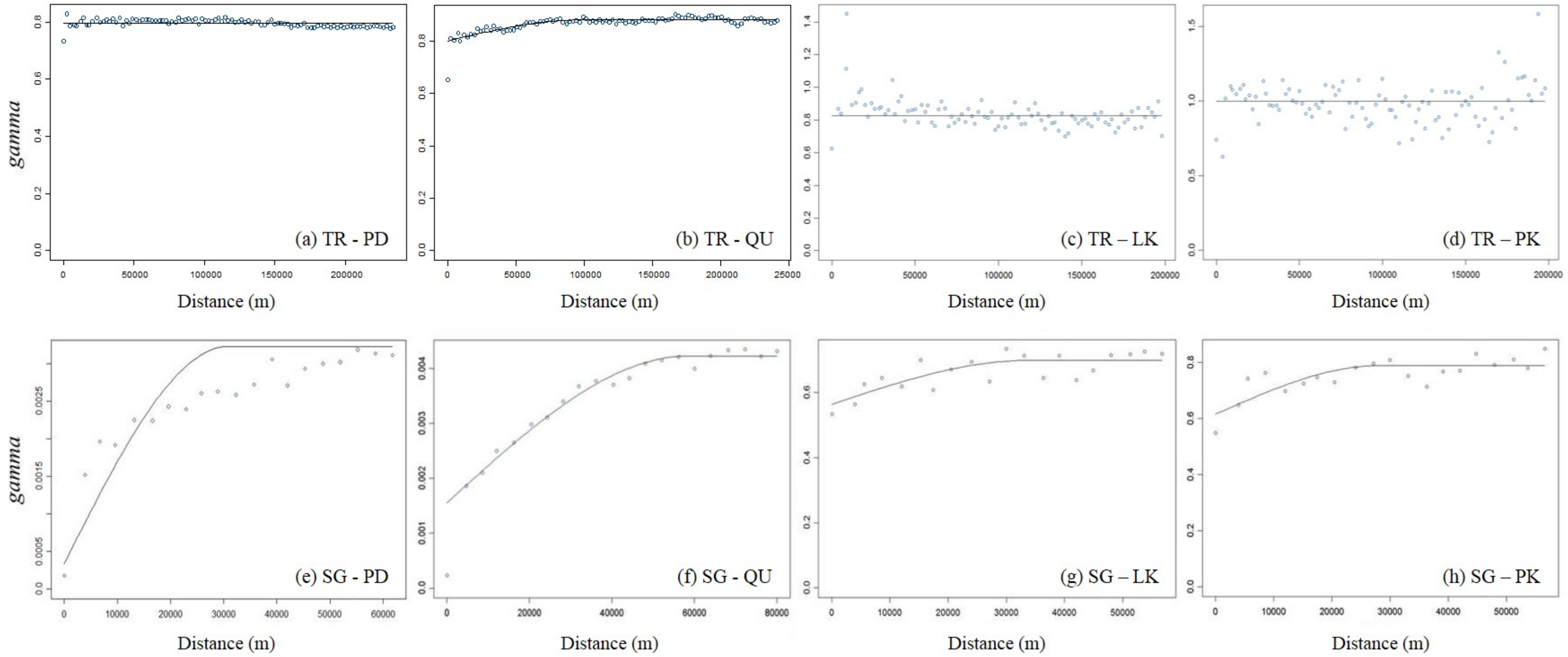

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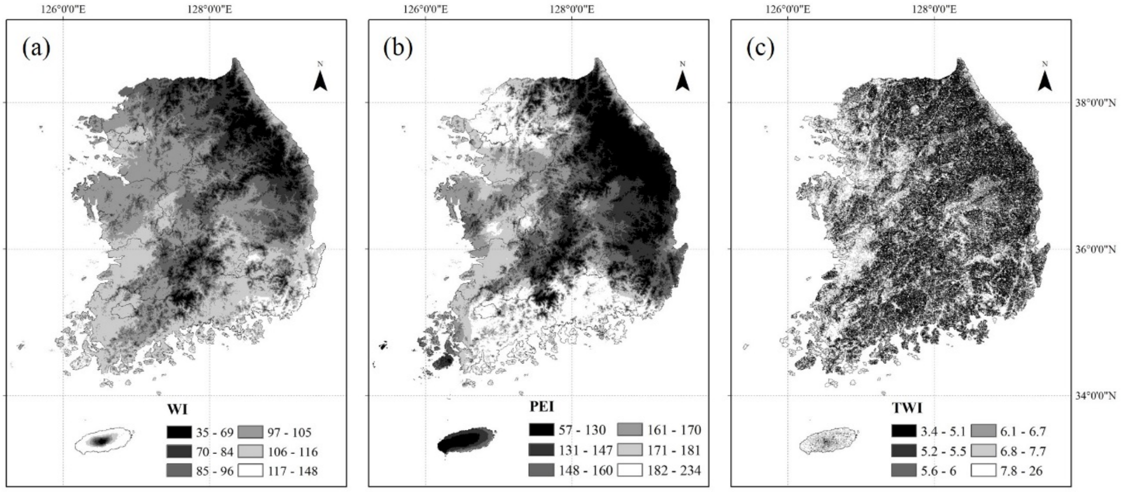

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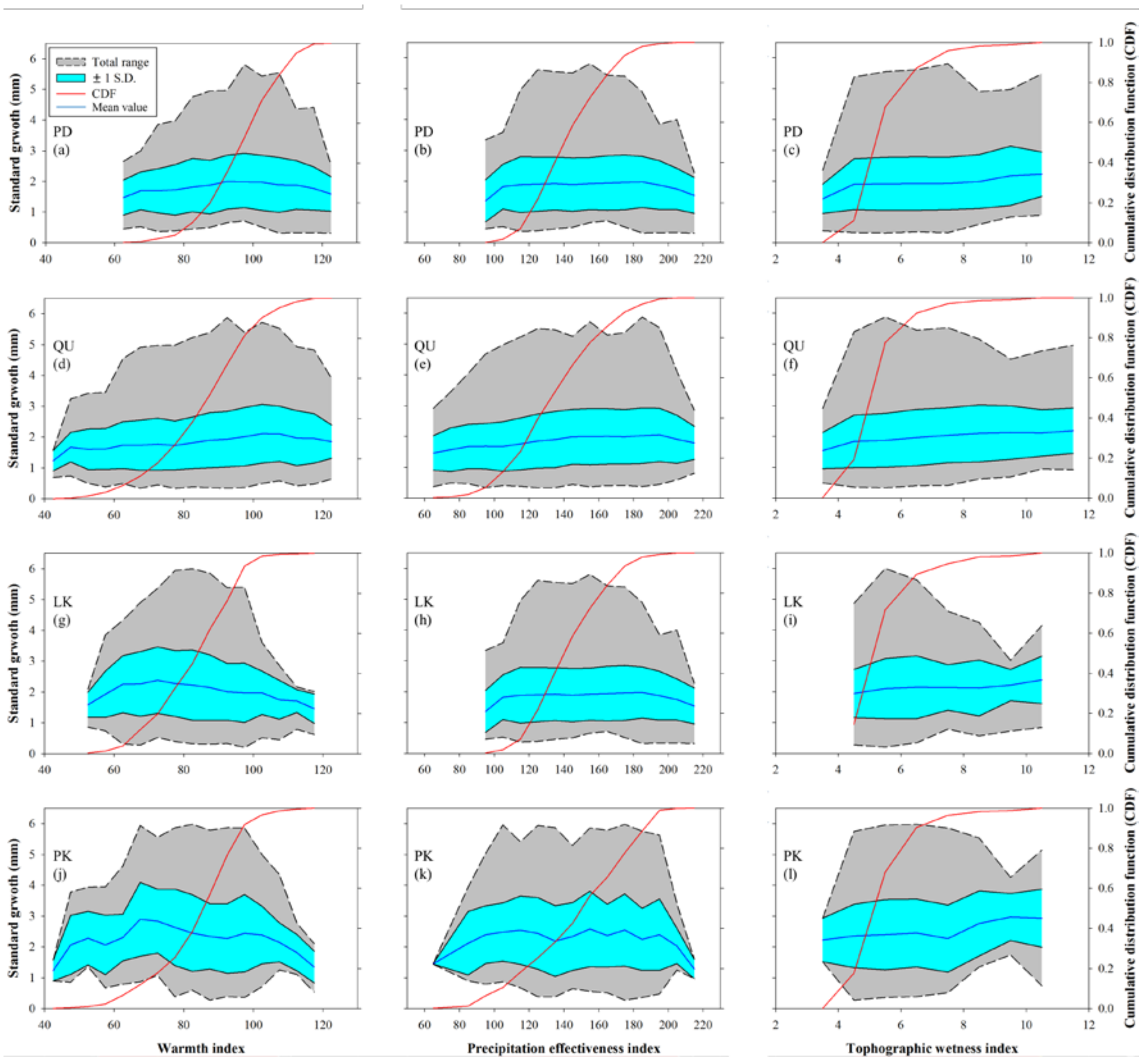

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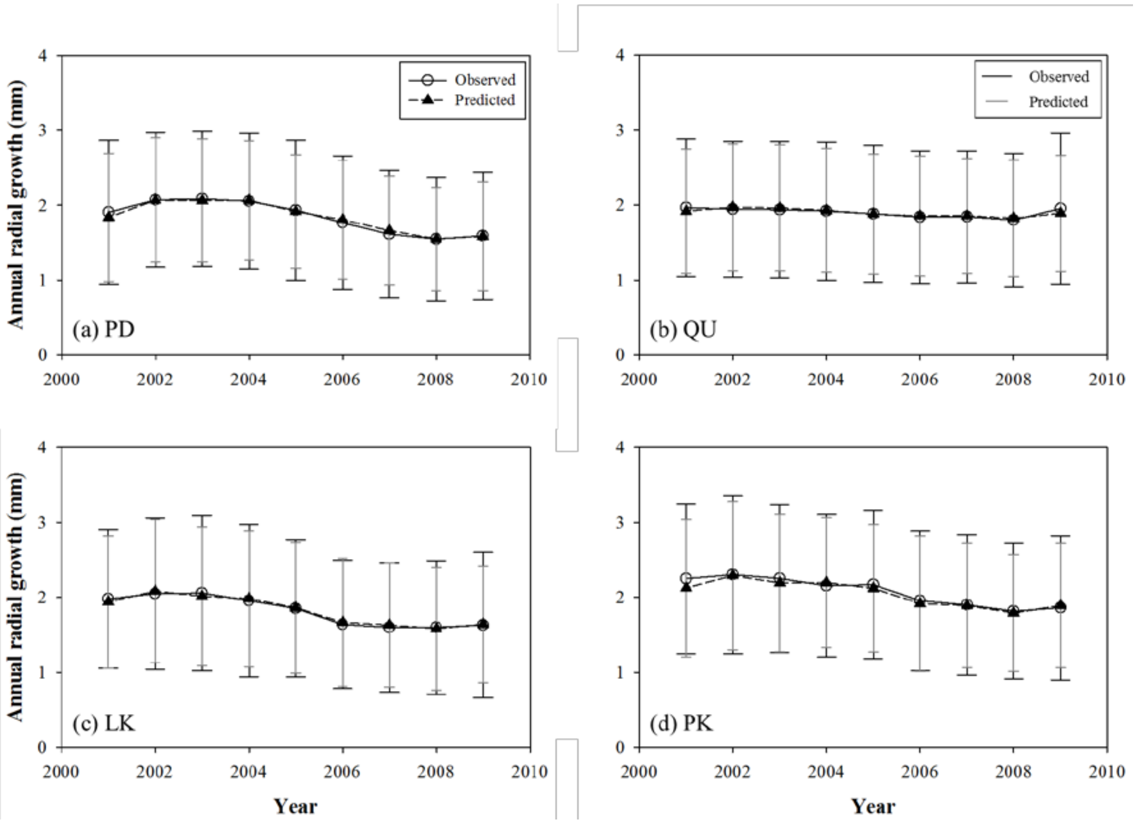
PD: *P. densiflora*, QU: *Quercus* spp., LK: *L. kaempferi*, PK: *P. koraiensis*



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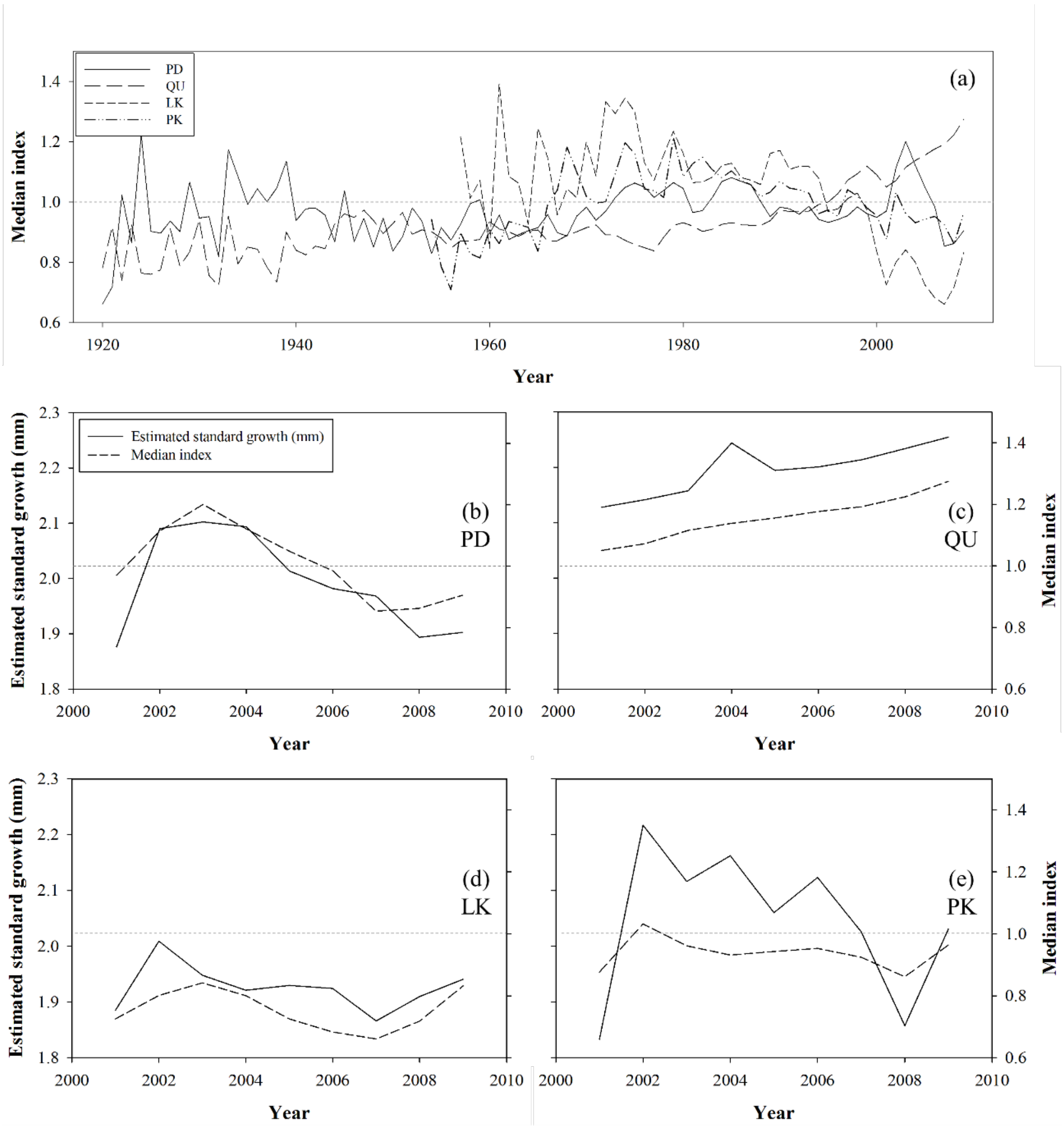

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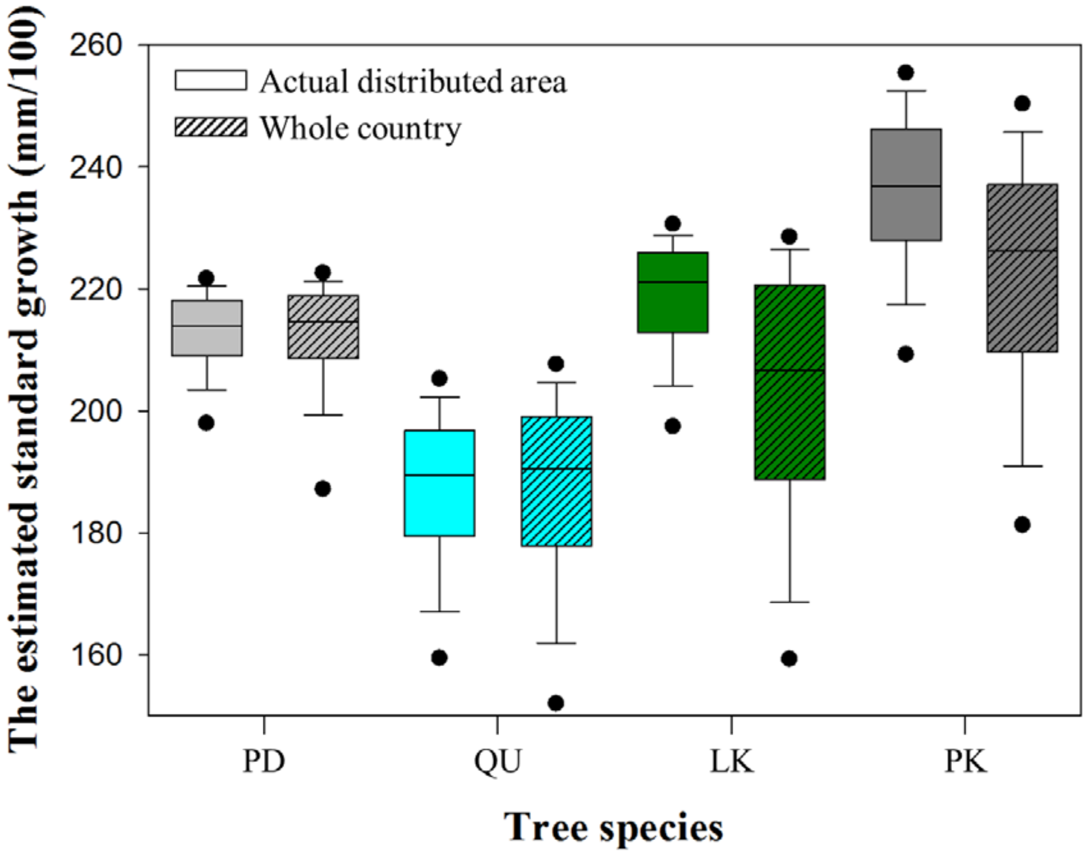

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PD: *P. densiflora*, QU: *Quercus* spp., LK: *L. kaempferi*, PK: *P. koraiensis*

Table 1. Descriptive statistics of size, and topographic and climatic factors of tree species in sample plots by tree species.

Factors	variables	Use	*Pinus densiflora*				*Quercus* spp.				*Larix kaempferi*				*Pinus koraiensis*			
			mean	min	max	[d]SD	mean	min	max	[d]SD	mean	min	max	[d]SD	mean	min	max	[d]SD
Age	Age (year)	Model	29.7	8.0	117.0	10.9	30.2	6.0	145.0	13.4	28.6	6.0	73.0	9.0	29.4	7.0	159.0	11.5
		Verify	32.5	11.0	127.0	11.4	31.4	12	237.0	12.7	31.2	14.0	74.0	8.5	30.8	19	92	9.3
Size	DBH (cm)	Model	19.0	6.0	75.0	7.8	16.7	6.0	53.0	6.7	22.0	6.0	61.0	6.6	17.9	6.0	59.0	8.2
		Verify	20.5	6.0	70.0	8.7	16.7	6.0	52.0	7.0	23.3	6.0	60.0	8.6	17.1	6.0	56.0	8.3
Topography	[a]TWI	Model	5.8	3.8	10.9	1.0	5.4	3.7	9.5	0.6	5.3	4.2	9.4	0.7	5.6	3.9	8.6	0.6
		Verify	5.8	3.9	10.5	1.0	5.7	3.7	10.5	0.9	5.9	4.5	10.3	1.1	5.6	4.1	10.3	0.9
Climate	[b]WI	Model	86.8	51.0	120.7	11.2	92.4	40.7	125.9	12.0	85.6	48.9	116.6	11.6	85.9	43.3	116.4	12.6
		Verify	94.9	53.2	123.1	12.2	89.1	47.1	130.5	13.9	84.9	51.8	111.0	11.0	86.5	47.2	116.4	11.1
	[c]PEI	Model	159.4	73.7	225.3	21.6	150.6	69.4	226.3	25.1	149.5	77.3	215.9	25.9	158.6	73.7	213.8	26.8
		Verify	144.6	74.9	209.1	22.4	141.8	63.7	209.9	26.4	139.8	77.5	206.1	26.9	155.9	86.1	200.4	28.2

[a]TWI: *Topographic wetness index*; [b]WI: *Warmth index*; [c]PEI: *Precipitation effectiveness index*; [d]SD: *Standard deviation*

Table 2. Parameter estimates for equation 1 ($\boldsymbol{\Delta r = a \cdot age^{b}}$).

Tree species	Coefficients	Estimate	Std. Error	*t* value	Pr > |t|	R^2
[a]PD	a	5.39	0.20	26.77	<0.001	0.09
	b	-0.30	0.01	-25.88	<0.001	
[b]QU	a	7.33	0.20	36.30	<0.001	0.14
	b	-0.39	0.01	-44.78	<0.001	
[c]LK	a	11.56	1.04	11.07	<0.001	0.20
	b	-0.48	0.03	-16.98	<0.001	
[d]PK	a	8.83	0.78	11.33	<0.001	0.18
	b	-0.39	0.03	-13.14	<0.001	

[a]PD: *P. densiflora*; [b]QU: *Quercus* spp.; [c]LK: *L. kaempferi*; [d]PK: *P. koraiensis*

Table 3. Parameter estimates and statistics for the GAM of *eSG*.

Tree species	Parameter	Estimate	Std. Error	*t* value	Pr > |t|
[a]PD	β_1	-0.0215	0.0057	-3.7915	0.0002
	β_2	3.8494	1.0969	3.5092	0.0005
	β_3	-0.0045	0.0016	-2.7826	0.0054
	β_4	1.6528	0.5394	3.0644	0.0022
	β_5	1.5165	0.7925	1.9136	0.0557
	Int	-110.5457	43.2428	-2.5564	0.0106
[b]QU	β_1	-0.0066	0.0032	-2.0723	0.0382
	β_2	1.9144	0.5699	3.3595	0.0008
	β_3	-0.0016	0.0010	-1.6342	0.1027
	β_4	0.6768	0.3093	2.1884	0.0287
	β_5	3.5160	0.7710	4.5605	0.0001
	Int	17.0048	17.0086	0.9998	0.3057
[c]LK	β_1	-0.0438	0.0089	-4.9246	0.0001
	β_2	6.5585	2.0585	3.1861	0.0001
	β_3	-0.0026	0.0016	-1.6111	0.1076
	β_4	0.7832	0.5353	1.4631	0.1439
	β_5	3.3452	1.3169	2.5402	0.0113
	Int	-93.1549	56.0178	-1.6629	0.0967
[d]PK	β_1	-0.0390	0.0102	-3.8066	0.0002
	β_2	5.5500	1.7755	3.1259	0.0018
	β_3	-0.0095	0.0027	-3.5296	0.0004
	β_4	3.1691	0.8738	3.6267	0.0003
	β_5	4.8319	1.9741	2.4476	0.0146
	Int	-231.5290	68.8332	-3.3636	0.0008

[a]PD: *P. densiflora*; [b]QU: *Quercus* spp.; [c]LK: *L. kaempferi*; [d]PK: *P. koraiensis*.

Table 4. Statistical evaluation of the radial growth model from 2001 to 2009.

Tree species	Mean RMSE	Mean R^2
[a]PD	0.5318	0.7132
[b]QU	0.4351	0.7297
[c]LK	0.5596	0.6742
[d]PK	0.6286	0.6536

[a]PD: *P. densiflora*; [b]QU: *Quercus* spp.; [c]LK: *L. kaempferi*; [d]PK: *P. koraiensis*.